DIFFUSE INTERSTELLAR BAND FORMATION IN DENSE CLOUDS*

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(Received 14 October, 1974)

Abstract. Measurements of the strengths of the diffuse interstellar bands at 4430, 5780 and 5797 Å show that the bands tend to be weak with respect to extinction in dense interstellar clouds. Data on 10 stars in the ϱ Ophiuchi cloud complex show further that the diffuse band-producing efficiency of the grains decreases systematically with increasing grain size. It is concluded that the diffuse bands are not formed in the mantles which accrete on the grains in interstellar clouds, but that they could be produced in the cores of grains or in some molecular species.

1. Introduction

Most speculation concerning the origin of the unidentified diffuse interstellar bands has centered on models in which the bands are produced in solid grains. This emphasis arises primarily because of the generally good correlation between band strengths and interstellar reddening, and because of various difficulties with other types of sources.

It is a general feature of absorption bands produced in small solid particles that several properties of the bands, such as the profiles or the central wavelengths, are subject to significant variations as a function of grain size and density of absorbers (see Aannestad and Purcell, 1973, and references cited therein). The purpose of the present study is to determine the dependence of the band strengths on mean particle size, in interstellar regions where it is believed that significant variations in grain size exist.

2. The Data

Photographic spectra were obtained of 13 stars embedded in dark clouds (i.e., stars in prominent cloud complexes having $E_{BV} \geqslant 0\overset{m}{.}50$), 14 stars lying behind less dense

* Paper presented at the Symposium on Solid State Astrophysics, held at the University College, Cardiff, Wales, between 9–12 July, 1974.

** Visiting Astronomer, Kitt Peak National Observatory, which is operated by the Associated Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

‡ Part of this study was carried out by the author at the University of Washington.

† Operated by the Associated Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Astrophysics and Space Science **34** (1975) 33–38. *All Rights Reserved*

portions of dark cloud complexes, and over 50 distant supergiants whose color excesses are due to their long lines of sight through several intervening clouds. The dark cloud stars in this study lie primarily in the ϱ Ophiuchi and Perseus II clouds. Spectra of 5 stars in IC 348, a very dense region in the Per II complex, were provided by Dr S. E. Strom.

Equivalent widths were measured for the relatively narrow diffuse features at 5780 and 5797 Å, and the central depth of the very broad 4430 Å band was determined for each star. Standard errors are estimated to be 15% of the true equivalent width of $\lambda\lambda$ 5780 and 5797 (or 10 mÅ for features weaker than 40 mÅ), and 1.5% of the continuum level for λ 4430.

Our data for distant supergiants and stars lying behind optically thin ($E_{BV} < 0\overset{m}{.}50$) portions of dark clouds were augmented by diffuse band measurements of other authors, care being taken in the case of λ 4430 to reduce the central depths to a common system by statistical techniques such as those described by Deeming and Walker (1967) and by Snow (1973).

3. Results

3.1. Comparison of Cloud Stars with Distant Supergiants

Plots of band strength against E_{BV} show that $\lambda\lambda$ 4430 and 5780 are systematically weakened in the dark cloud stars, as indicated in Figure 1, where it is seen that most dark cloud stars lie well below the mean correlation based on distant supergiants. This is consistent with Wampler's (1966) study of λ 4430, but not with the recent finding of Bromage and Nandy (1973) that the band strengths in the VI Cygni OB association (Cygnus OB2) correlate normally with E_{BV}. It should be pointed out, however, that the VI Cygni association is in the galactic plane and lies nearly 2 kpc from the Sun (Walborn, 1973), whereas the ϱ Oph and Per II complexes are considerably nearer and are well out of the plane. Hence the large color excesses in VI Cygni are probably due to the long line of sight through foreground material, and not to extinction in dense clouds like the ϱ Oph cloud or Per II. Polarization data (Coyne *et al.*, 1974) show nothing unusual for the grains in the direction of VI Cygni, whereas for the ϱ Oph region (Carrasco *et al.*, 1973) and IC 348 (Strom, 1974) it is evident that grain sizes increase with increasing cloud density. Hence the conclusions of Bromage and Nandy concern an interstellar region unlike those considered in the present study.

Plots of λ 5780 vs λ 4430 and λ 5797 vs λ 5780 show no systematic deficiency of one band with respect to the others in dark clouds, as compared with the distant supergiants.

3.2. The ϱ Ophiuchi Complex

We have diffuse band data for 10 of the stars in the ϱ Oph dark cloud complex for which Carrasco *et al.* (1973) give photoelectric and polarimetric data pertaining to

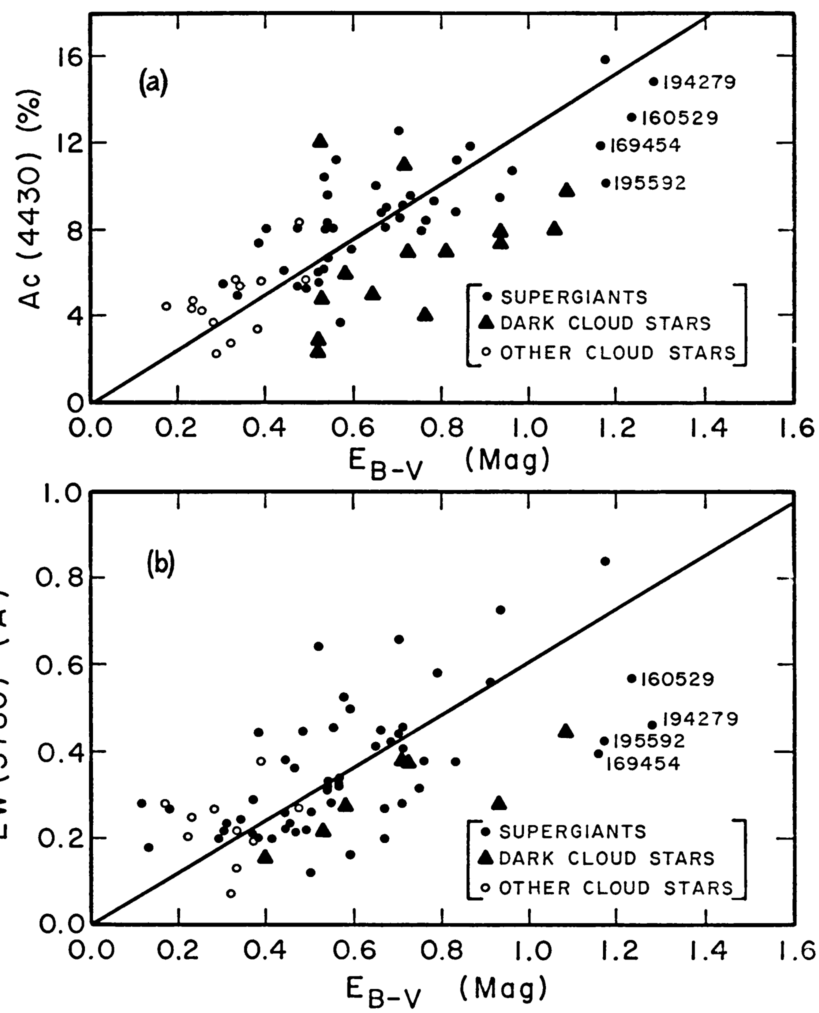

Fig. 1. (a) The correlation of λ 4430 central depth with color excess. The solid line indicates the mean correlation based on the distant supergiants alone, forced through the origin. Most of the stars in dense clouds (triangles) lie well below this line, indicating that λ 4430 in dense clouds is weak with respect to color excess. (b) The corresponding plot, showing the equivalent width of λ 5780 vs color excess. The same trend is evident as for λ 4430; the correlation between these two bands appears the same, both in and out of dark clouds (see text).

the mean interstellar grain size. It is found that two indicators of grain size, the ratio E_{VK}/E_{BV} (roughly the ratio of total to selective extinction) and the wavelength of maximum polarization, both increase with increasing optical length (as indicated by E_{VK}), showing that the mean grain size increases with increasing cloud density. This is consistent with the suggestion of Routly and Spitzer (1952) and the more recent conclusions of Cohen (1973) and Wallerstein and Goldsmith (1974) that grains in interstellar clouds can grow by accreting atoms onto their surfaces, since the greatest grain growth would be expected in the densest portions of clouds.

Our data show that the diffuse band-producing efficiency of the grains in the ϱ Oph complex is greatest in the outer portions of the cloud, and that the band strength per grain (as indicated by the ratio S/E_{VK}, where S is the band strength in appropriate

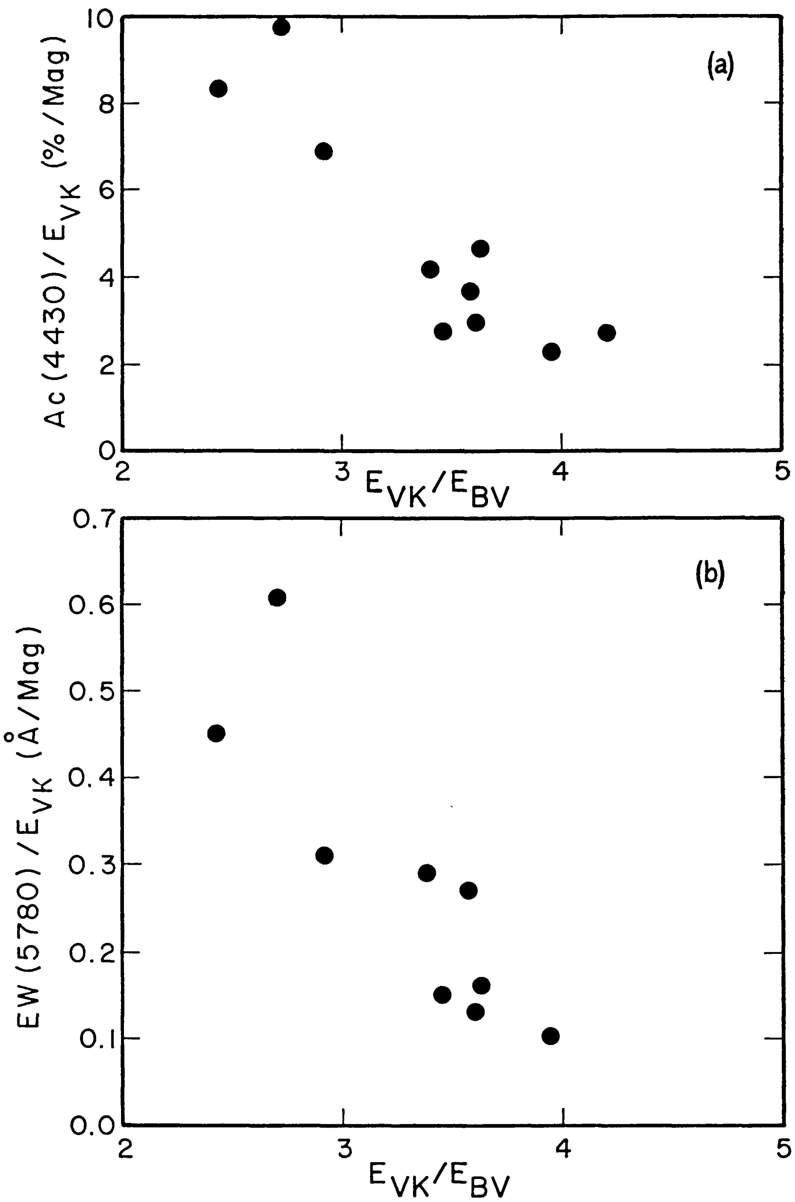

Fig. 2. (a) The strength of λ 4430 per grain plotted against the ratio of total to selective extinction for stars in the ϱ Oph cloud complex. It is seen that in the cloud interior, where mantles have apparently accreted onto the grains, the diffuse band-producing efficiency of the grains is lowest. (b) A similar plot, showing the systematic decrease of λ 5780 strength per grain with increasing ratio of total to selective extinction. The trend for both bands is similar if other indicators of grain size, such as the wavelength of maximum polarization, are plotted in the horizontal axis.

units) decreases systematically with increasing grain size. In Figure 2 is shown the dependence of the strengths per grain of $\lambda\lambda$ 4430 and 5780 on the ratio of total to selective absorption. The trend is the same if λ_{max}, the wavelength of maximum polarization, is plotted in place of E_{VK}/E_{BV}. Data from Merrill *et al.* (1937) on the strength of the diffuse feature at 6284 Å show that its strength per grain also decreases with increasing grain size for the 5 ϱ Oph cloud stars included in that study.

Our data are of insufficient quality to allow detailed inferences to be made concerning possible variations in the profiles of the diffuse bands as a function of grain size. No gross effects are seen, however; no shift can be seen in the central wavelength of λ 4430 to an upper limit of roughly 5 Å (considerably less for the more narrow bands), and no prominent emission features appear. It would be of very great interest to make a high quality study of the profiles of the diffuse bands in regions containing peculiar dust grains.

4. Discussion

The deficiency of diffuse band strengths in dark clouds and the systematic decrease of band-producing efficiency with increasing particle size strongly imply that the bands are not produced in the mantles of interstellar grains. They could originate in the cores of grains, assuming that the optical properties of the cores could be sufficiently smothered by the accretion of mantles in dense cloud interiors, or they could be produced by some agent which is most abundant in the outer portions of interstellar clouds. This agent could be a distinct population of grains, or some molecular species.

The possibility that some or all of the diffuse bands are produced by molecules has been generally disregarded. It is interesting to note, however, that the findings in the present study would be consistent with a band origin in a species of molecule which either requires a substantial ultraviolet flux for formation or contains hydrogen, since molecules of these kinds would not be formed efficiently in the interiors of dense clouds. For example, the data of Cohen (1973) show that both CH and CH^+ are most abundant with respect to E_{VK} in the outer portions of the ϱ Oph complex. Our observed lack of gross variations in band profiles with grain size would also be consistent with a molecular origin. The suggestion of Herzberg (1967) that predissociation transitions could produce the unstructured breadth of the diffuse bands may be unlikely, however, as shown by arguments such as those of Wilson (1964) that any process which destroys the band carrier requires an unreasonably high formation rate. On the other hand, there are kinds of molecular transitions which could take place in simple molecules consisting of cosmically abundant elements, which would produce broad absorption bands without detectable fine structure, and which would not destroy the molecules (Smith, 1974).

Acknowledgements

We acknowledge with pleasure the kind assistance of Dr S. E. Strom, who provided diffuse band data on 5 stars, and Dr G. Wallerstein, who provided plates of some of the ϱ Oph cloud stars. One of us (T.P.S.) carried out a portion of this study while he was a Predoctoral Research Associate at the University of Washington, where this work was supported in part by the Graduate School Research Fund of the University of Washington, and in part by National Science Foundation grant GP28881. The work done at Princeton was supported by National Aeronautics and Space Administration contract NAS5-1810.

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